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ATTENUATION OF MUZZLE BLAST USING CONFIGURABLE MUFFLERS

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JANUARY 1989

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The noise attenuation obtained by using gun silencers configured with different baffle arrangements was investigated. The muffler sizes varied from one to nine bore-and-chamber volumes. Both the number and the spacing of the internal baffles were changed to study the attenuation response. The near-field and far-field overpressures were measured at different polar angles about the boreline and attenuation values were obtained. Gages installed through the silencer bodies were used to obtain interior pressures. A model was introduced that uses ~~utilizes~~ a simple assumption together with an established blast field prediction technique to give estimates of lower bound attenuation values. It was found that for medium size mufflers and larger, the measured noise attenuation is much greater than predicted by the operational muffler model. A one-dimensional model of the flow was also developed and utilized to predict peak baffle pressures for optimum design of baffle structures in the inlet chamber. In addition, a new silencer design for use with saboted projectiles is presented. Keywords:

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I. Introduction

The 25mm M242 cannon, the main armament of the Bradley Fighting Vehicle, generates annoying noise levels during firing. The Ballistic Research Laboratory has proposed a research and development program for a fieldable noise attenuator. The muffler should not interfere with normal training maneuvers or firing operations of the weapon. Ideally, the muffler should have minimum mass and effectively attenuate the muzzle blast noise to or below a specified level. For optimally configured mufflers, the larger the volume, the greater the noise attenuation. However, greater muffler volume will result in a heavier muffler structure. These conflicting requirements, reasonable noise attenuation and light muffler weight, lead to the following objective: to study noise suppressors with enough internal volume to obtain sufficient noise attenuation, yet when designed for minimum weight, are light enough to allow training with minimal interference.

The capability to predict both internal and free-field overpressures for mufflers is another objective. Accurate predictive methods would greatly facilitate noise attenuator design. No adequate, easily used model of the flow in a muffler has yet been developed, although a prediction of the external blast field of the weapon is possible if the gas exit conditions at the muffler are known. The blast field overpressure is predicted by an approach that uses blast wave scaling theory for variable energy deposition rates into the ambient air, coupled with the theory of blast waves generated by asymmetrically initiated charges.[1,2,3,4] A fundamental length that determines the scale of the muzzle blast is obtained from the analysis. In terms of the exit conditions, the scaling length, ℓ, is proportional to the square root of the peak energy efflux from the bore of the gun or, if the gun mounts a muzzle device, from the muzzle device exit hole for the projectile. The peak overpressure of the blast wave is also dependent upon the polar angle, θ, that is measured from the boreline. The muzzle blast is much stronger in front of the gun than behind. Thus, the scaling equation is obtained:

$$P = P[(r/\ell), \theta] \tag{1}$$

where P is the peak overpressure divided by the ambient pressure and r is the distance from the muzzle. For maximum noise attenuation, the peak energy efflux from the muffler projectile hole must be minimized. The exit-hole diameter for the silencer, the maximum exit pressure from the silencer, and the propellant gas exit velocity should all be minimized. The last two objectives are accomplished by increasing the internal volume of the device and using internal baffling to promote viscous processes and maximize heat transfer from the propellant gases. For the study of these devices, it is assumed that the ratio of the internal volume to the gun bore and chamber volume best characterizes their ultimate

[1]Fansler, K. S., and Schmidt, E. M., "The Relationship Between Interior Ballistics, Gun Exhaust Parameters and the Muzzle Blast Overpressure," AIAA Paper 82-0856, AIAA/ASME 3rd Joint Thermophysics, Fluids, Plasma and Heat Transfer Conference, St. Louis, MO, 7-11 June 1982.

[2]Heaps, C. W., Fansler, K. S., and Schmidt, E. M., "Computer Implementation of a Muzzle Blast Prediction Technique," *The Shock and Vibration Bulletin*, Part 1, published by The Shock and Vibration Center, Naval Research Laboratory, 22-24 October, 1985, pp. 213-230.

[3]Fansler, K. S., "Dependence of Free Field Impulse on the Decay Time of Energy Efflux for a Jet Flow," *The Shock and Vibration Bulletin*, Part 1, published by The Shock and Vibration Center, Naval Research Laboratory, 22-24 October, 1985, pp. 203-212.

[4]Smith, F., "A Theoretical Model of the Blast from Stationary and Moving Guns," *First International Symposium on Ballistics*, Orlando, Florida, 13-15 November 1974.

attenuation capabilities. Accordingly, the mufflers will be designated by their volume in terms of gun volumes. A gun volume is the sum of the bore and chamber volumes.

Insufficient research has been conducted to develop adequate models for the noise attenuation properties of mufflers. Linear gasdynamics theory has been used,[5] but with the high pressures and supersonic flow encountered in the muffler, nonlinear gasdynamics should be applied to this problem. One of the more promising nonlinear approaches is given by Mori et al.[6] They published experimental data and an analysis for the attenuation of a shock wave as it passed through a series of baffles having circular orifices along the axis. In the present work, a similar approach will be taken when considering the flow onto the first or inlet baffle of the silencer. The cross-sectional area of the silencer can be varied to determine how the stagnation pressure changes at the exit or inlet baffle. The stagnation pressure determines the mass flow through the projectile hole and if the initial reflected pressure on the baffle is the maximum value, it also sets structural requirements on the baffle.

As the use of saboted projectiles increases, a muffler design compatible with this type ammunition will be necessary. For Maxim silencers and their conventional derivatives, the exit baffle is located at the end of the silencer. The exit hole is kept as small as possible to limit the energy efflux and thus, according to theory, minimize the peak blast overpressure. Immediately after the spinning projectile exits the muzzle, centrifugal force separates the sabots from the subprojectile. The projectile and discarding sabot components must pass through the exit hole without deviation. To do so, the exit hole must be exceedingly large, which results in increased blast noise. However, if a muffler could be designed with the exit hole located close to the muzzle, the exit hole diameter could be made much smaller. In Figure 1, a schematic is shown of such a muffler attached to a threaded gun muzzle. Once the saboted projectile exits the muzzle, the propellant gases are free to expand. The exit hole for the saboted projectile is placed as near as possible to the muzzle to reduce the necessary size, yet far enough away to take advantage of the decrease in the axial energy flux density with distance from the muzzle. This decrease is associated with the expansion of the propellant gas to the outer shell of the muffler. The amount of energy efflux passing through the exit hole would decrease with distance from the muzzle until the reflected compression wave from the muffler cylinder wall reached the boreline axis. The portion of the flow not initially passing through the exit hole travels toward the perforated baffles in the accumulation chamber. Although Figure 1 illustrates a silencer with two perforated baffles, more baffles might provide better performance. Optimum conditions are found by experiment or numerical simulation. With this system of perforated baffles inducing viscous processes and partially reflecting shock waves, the baffles can be designed so that the accumulation chamber peak pressures are markedly reduced compared to a muffler of equal volume with no perforated baffles. With the loads on the silencer reduced, the mass of the structure can also be reduced. Furthermore, a properly tailored system of perforated baffles will also reflect pressure waves of an optimum amplitude to avoid high pressure transients at the exit hole. Such undesirable pressure waves of short duration could result in higher peak pressures external to the silencer. Also, the angle and shape

[5] Davis, D. D., Stokes, G. M., Moore, D. and Stevens, G. L., "Theoretical and Experimental Investigations of Mufflers, with Comments on Engine Exhaust Muffler Design," NACA Report No. 1192, 1954, pp. 829-875.

[6] Mori, Y., Hijikata, K., and Shimizu, T., "Attenuation of Shock by Multi-Orifice," *Proceedings of the 10th International Shock Tube Symposium*, Japan, 1975.

of the exit cone is designed to allow the discarding sabot components to pass without interference.

II. Experiment

All experiments were performed with a 25mm M242 cannon shooting M-793 TP-T ammunition. Some relevant values for the experiments are the following:

$$C = 0.092 \text{ kg}$$

$$RT = 975{,}000 \text{ m } /\text{s}$$

$$k = 1.25$$

$$U = 0.00101 \text{ m}$$

$$m = 0.185 \text{ kg}$$

$$E = 203 \text{ kJ}$$

Here C is the propellant charge mass, m is the projectile mass, RT is the specific energy or the force of the propellant, k is the specific heat ratio, U is the internal volume of the gun, and E is the available propellant energy at projectile exit from the gun muzzle. The cannon bore length is approximately 80 calibers.

It is not feasible to attach a large volume muffler on a 25mm cannon since the additional mass would interfere with normal training operations. The scope of this study is therefore restricted to mufflers with small (less then ten) gun volume values. The study commenced with the testing of a very small (approximately one-gun-volume) muffler in which the number of baffles and spacing between baffles could be varied. This muffler, set up for a near-field test, is shown in Figure 2. Free-field gages were placed 10, 45, 90, 135, and 170 degrees from the boreline and 50 calibers from the muffler exit hole. A drawing of this muffler is shown in Figure 3. Internal baffles are threaded into the muffler so their positions can be varied continuously. Two piezoelectric pressure transducer gages placed at the positions shown monitor the internal pressures during firing. Table 1 describes the various configurations. The silencer internal length is the distance between the front of the muzzle plate and the rear of the exit baffle. The inlet length is the distance between the front of the muzzle plate and the back of the first internal baffle, which is known as the inlet baffle. Subsequent baffles are equally spaced between the inlet baffle and the exit baffle. For scaling purposes, the length in calibers can be obtained by dividing the length by the bore diameter, which is 2.5 cm.

Figure 4 shows the gun with the standard muzzle brake attached. Comparisons between overpressure values for the muffler and the standard muzzle brake were made. Data were recorded on Nicolet scopes and processed on an HP9845 microcomputer and the LFD/VAX computer system.

Table 1. Configurations Tested for the One-Gun-Volume Muffler

Configuration Number	Silencer Internal Length (cm)	Inlet Length (cm)	Number of Baffles	Spacing Between Baffles (cm)
1	26.8	-	0	-
2	"	10.3	1	-
3	"	14.1	1	-
4	"	17.9	1	-
5	"	10.3	2	8.2
6	"	10.3	3	5.4
7	"	10.3	4	4.1
8	23.0	-	0	-
9	"	8.8	1	-
10	"	13.8	1	-
11	"	8.8	2	7.0
12	"	8.8	3	4.8
13	19.2	-	0	-
14	"	6.0	1	-
15	"	11.0	1	-
16	"	6.0	2	6.5

Derived from a design patented by Bell Laboratories,[7] a six-gun-volume muffler was also tested (Figure 5). The patent applicant claimed that the importance of a cross-sectional area diminished toward the front end, therefore the size and weight of a muffler could be reduced without seriously compromising noise attenuation. The first section, or stage, of the muffler consisted of a larger chamber 6.6 calibers in diameter and 7.8 calibers in internal length. The second stage utilized the 3.5 caliber diameter body of the smallest muffler. When used, the internal baffles were equally spaced within the second stage.

A conventional nine-gun-volume muffler, shown in Figure 6, was also studied. The internal muffler length was 18.5 calibers and the internal diameter was 6.6 calibers. The number and position of the baffles could be varied by using spacer rings. In terms of gun volumes, all these mufflers are small compared to the silencers used on rifles or pistols.

It is anticipated that a saboted training round for the 25mm cannon will be fielded soon. To study the expected performance of sabot-capable mufflers, the configuration of the nine-gun-volume muffler was modified as shown in Figure 7. This is a prototype design which, although not compatible with saboted projectiles, was used to verify the concept. This device was also used to experiment with the axial placement of the exit hole, relative to the gun muzzle, and the degree of baffle perforation. The perforated spoke baffle is secured inside the outer cylinder by retaining rings that are in turn clamped between the

[7] Mason, W. P., "Silencer," U. S. Patent No. 2448382 assigned to Bell Laboratories, August 31 1948.

muzzle plate and the exit baffle. The nonperforated tube has a shoulder that permits it to be held securely in place between the perforated spoked baffle and the exit baffle. The spoked baffle for the configuration tested had 60 percent of the cross-sectional area removed to allow propellant gas to pass into the accumulation chamber.

III. Results and Analysis

The one-gun-volume muffler was configurable in a more flexible manner than the larger mufflers since its internal length could also be changed. Cooke and Fansler[8] give a comparison of attenuation levels for some configurations with different internal lengths. These noise attenuation levels were insensitive to the internal length. Usually, the attenuation increases with increasing volume. However, as discussed by Cooke and Fansler,[8] a one-dimensional model can be utilized to approximate the flow in the first, or inlet, chamber. The model can also calculate the stagnation pressure at the inlet baffle. If a one-dimensional model of the flow is assumed, the peak pressure at the exit baffle should not vary with distance. The peak energy efflux is determined by the reflected pressure at the exit baffle and therefore the attenuation should not vary with the length. Figure 8 shows results for the muffler configured to the longest internal length while the inlet length is varied. Again, there are no discernable differences in overall noise attenuations. Similar results are obtained when the number of internal baffles are varied. As the length of the muffler could be varied only over a narrow range, no data could be obtained for lengths over 12 calibers. It is anticipated that the attenuation will increase for significantly longer lengths.

The two larger volume mufflers were not studied in as much detail. For the six-gun-volume muffler, the number of baffles was varied only in the second stage, smaller diameter, part of the muffler. Figure 9 shows the attenuation at first increases with the addition of baffles, then reaches a maximum for three internal baffles. For the nine-gun-volume muffler, Figure 10 shows the attenuation obtained for different numbers of baffles. Again, the attenuation increases and then decreases with increasing number of baffles. The distance between baffles for the most effective nine-gun-volume muffler (1.7 calibers) was substantially less than for the six-gun-volume muffler (3 calibers). Figure 11 shows the exit baffle pressures for some of the baffled configurations. By increasing the number of baffles, the peak baffle pressure is not only lowered, but occurs at a later time. For the multi-baffled configuration, the exit baffle pressure increases in a rather smooth manner and appears isolated from the pressure transients that are occurring in the inlet chamber. Neither the one-dimensional treatment of Mori,[6] which yields the peak transient reflected wave at the baffle, nor accoustical approaches such as used by Davis,[5] would yield the peak pressure for this pressure wave which increases slowly with time.

The one-dimensional model was explored at some length for the smallest volume muffler.[8] The validity of the model can be further tested using the largest muffler with no internal baffles. Figure 12 is a plot of the exit baffle peak pressure versus the muffler internal diameter. The model prediction shows that the reflected pressure from the baffle

[8] Cooke, C. H., and Fansler, K. S., "Numerical Simulation of Silencers," *Proceedings of the 10th International Symposium on Ballistics*, San Diego, CA, 27-28 October 1987.

should decrease with increasing diameter. The experimental pressure values are somewhat lower than predicted at the smaller diameter but agree well for the larger diameter. Initial pressure in the muffler was assumed to be atmospheric and, for ease of calculation, the specific heat ratio of the propellant gas was also assumed as an initial condition. However, these ambient conditions would be modified by the precursor from the gun bore, especially in the smaller noise attenuators. Although the assumptions lead to a crude model, the agreement is adequate and the model can be used as a tool to evaluate muffler performance.

As stated previously, no adequate model of the muffler flow processes has been developed. However, a model that represents an extreme simplification of the muffling processes could serve as a starting point.[9] The flow into the muffler is reminiscent of a Joule expansion into a closed container where the equilibrium temperatures before and after the process are equal. In a closed container used for a Joule expansion, baffles could hasten the process toward equilibrium conditions and minimize pressure peaks at the end wall of the expansion section. The stagnation pressure for the ideal gas assumption is

$$p = (k-1)E/U \qquad (2)$$

where

U = total internal volume of silencer plus bore and chamber volume

E = available energy of the gas when projectile exits muzzle

If we neglect the energy of the gas that has exited before the maximum pressure at the exit baffle occurs, the pressure should be inversely proportional to the total volume. Figure 13 shows the peak pressure at the exit baffle versus total volume for the more effective muffler configurations. With the exception of the six-gun-volume muffler with one internal baffle, the peak exit baffle pressures are lower than the Joule model results. These lower pressures may be partly explained by the filling and emptying processes occurring for each chamber. The chambers in the muffler that are closer to the muzzle have higher pressures. For the more effective mufflers, the pressure in the entrance chamber is large compared with the pressure at the exit baffle. Also, for the more effective configurations, a significant amount of the propellant gas escapes from the exit hole before the pressure peaks on the baffle. The escaped gas is unavailable to contribute to the internal pressure. Heat transfer to the muffler would also lower the temperature of the exhaust gases and, according to the perfect gas law, lower the pressure inside the muffler by a proportional amount. A recent test performed on a fieldable version of the two-stage muffler utilizing thermocouples showed that the propellant gases transferred almost 25 percent of their energy to the muffler. Since the muffler has approximately twice the surface area of the gun tube and the gas is held in the barrel much longer with the muffler attached, the heat transfer to both the muffler and the barrel should also be significantly increased. However, the reduction in peak energy efflux would depend upon when the peak occurred in the exhaust cycle. The later the peak occurs, the more time the gas has to transfer a significant amount of its energy to the muffler and the more important the role of heat transfer in attenuating gun noise.

[9] Schmidt, E. M., Private communication, 1985.

According to the scaling law discussed earlier,[1,2,3] the muzzle-blast peak overpressure at a certain polar angle depends only on the peak exit-baffle pressure. Figure 14 gives a plot of the peak free-field overpressure at 90 degrees to the bore axis versus the baffle peak pressure. Some nonbaffled configurations are also given since this analysis should cover these configurations also. The largest variations from the prediction curve occur for the six-gun-volume data. All data values for the two-stage configurable muffler are low. The more effective configurations for the larger mufflers fall below the prediction curve. The more effective configurations, as illustrated by Figure 11, also have their peak pressures occurring at later times than the least effective configuration, thus allowing the gas to expand, cool and transfer more energy to the muffler surfaces in the form of heat. The energy efflux rate should therefore be lower than predicted by the Joule assumption.

The Joule model can also be used to predict the free-field peak overpressure by utilizing the scaling predictions. Figure 15 shows the peak overpressure versus volume for both experiment and model prediction. Agreement of the data with the model is good for the smallest volumes but for the larger volumes, the model predicts significantly larger values. Again, the larger value for the prediction is expected because the presence of the baffles allows significant outflow before the maximum value of the energy efflux is reached. From the limited data for muzzle blast peak overpressure versus volume, a least-squares line connecting the most effective configurations can be constructed. This line shows the pressure decreasing significantly faster than predicted by the Joule model. This trend should continue for larger mufflers as the inlet-chamber-to-exit-chamber pressure differentials, the extraction of heat and the viscous effects would increase with the volume.

The muffler design for saboted rounds has not yet been well-studied, but a small amount of data has been collected from limited experiments. An idealized design is shown in Figure 1 and the nine-gun-volume muffler modified to study the expected performance of the sabot-capable muffler is shown in Figure 7. Such a representative configuration was tested in the far-field along with some other configurations representing the Maxim or conventional design. The test was performed jointly with personnel from the U. S. Army Construction Engineering Research Laboratory (CERL) located in Champaign, Illinois. Microphones were placed 75 metres to the sides and rear of the gun muffler. The exit hole was placed 6.3 calibers from the muzzle plate. The perforated baffle was located 2 calibers beyond the exit hole and had 60 percent of its area removed (a clear area fraction of 0.6). The most effective configurations, according to near-field results, for the nine-gun-volume muffler and the six-gun-volume muffler were tested. The nine-gun-volume muffler without any internal baffles was also included. The noise generated was referenced to the noise produced with the standard brake. The values given in Table 2 are in SEL A-weighted decibels. The saboted projectile configuration performed well considering that the exit hole location, baffle placements, baffle number, and clear area fractions of the perforated baffles have not yet been optimized.

The 25mm automatic cannon is equipped with a muzzle brake/flash hider to moderate the gun recoil impulse. To avoid damage to the gun carriage, the impulse generated by the cannon with muffler should be no larger than the impulse generated with the muzzle brake attached. Accordingly, it is necessary to consider the amount of recoil expected from these devices. The mufflers were fired on a free recoil mount and the momentum index

Table 2. Far-Field Noise Attenuation with Prototypes (dB-A)

Muffler description	Side (Average)	Rear
Muffler (nine-gun-volume)	12.1	19.3
Muffler (nine-gun-volume) No internal baffles	9.1	14.4
Muffler (nine-gun-volume) Saboted projectile conf.	10.1	19.2
Muffler (six-gun-volume)	10.6	22.2

was measured. The momentum index, H, is

$$H = (I - I')/G \tag{3}$$

where I is the recoil impulse of the gun barrel with a bare muzzle, I' is the recoil impulse of the gun with the device attached, and G is the impulse given the bare muzzle gun by the propellant gases. The momentum index is a measure of the effectiveness of the muzzle brake in reducing the impulse given by the propellant gases and is discussed at length by Fansler.[10] If Euler inviscid flow and no heat transfer are assumed, the predicted momentum index for a simple muffler would be zero. Figure 16 shows a plot of the momentum index versus the gun volume of some mufflers. Obviously, the muffler also functions as a muzzle brake. The nine-gun-volume and six-gun-volume mufflers in their most effective noise attenuation configurations yield momentum indices approaching that of the standard muzzle brake ($H = 0.43$). The nine-gun-volume muffler without any internal baffles yields a smaller value than the one-gun-volume muffler. As discussed earlier, heat transfer measurements on the two-stage muffler in the most effective noise attenuation configuration show that almost 25 percent of the propellant gas energy is lost through heat transfer to the muffler. Perhaps an additional ten percent is lost because of increased heat transfer to the barrel itself. According to the perfect gas law, the pressure should also decrease by an equal percentage. The impulse upon the gun is proportional to the propellant gas velocity at the exit hole but the local sound velocity varies as the square root of the pressure. Extraction of the propellant gas energy reduces the pressure by 35 percent, which results in the sound velocity of the gas and therefore the impulse from the propellant gas being reduced by approximately 20 percent.

IV. Summary and Conclusions

For the smallest muffler, the presence of any internal baffling does not significantly improve the noise attenuation performance. Furthermore, the noise attenuation varied little when the volume was reduced by approximately 25 percent. The diminishment of pressure transients and general pressure levels observed in the exit-baffle chamber when

[10] Fansler, K. S., "A Simple Method for Predicting Muzzle Brake Effectiveness and Baffle-Surface Pressure," ARBRL-TR-02335, U.S. Army Ballistic Research Laboratory, Aberdeen Proving Ground, Maryland, June 1981. (AD A102349)

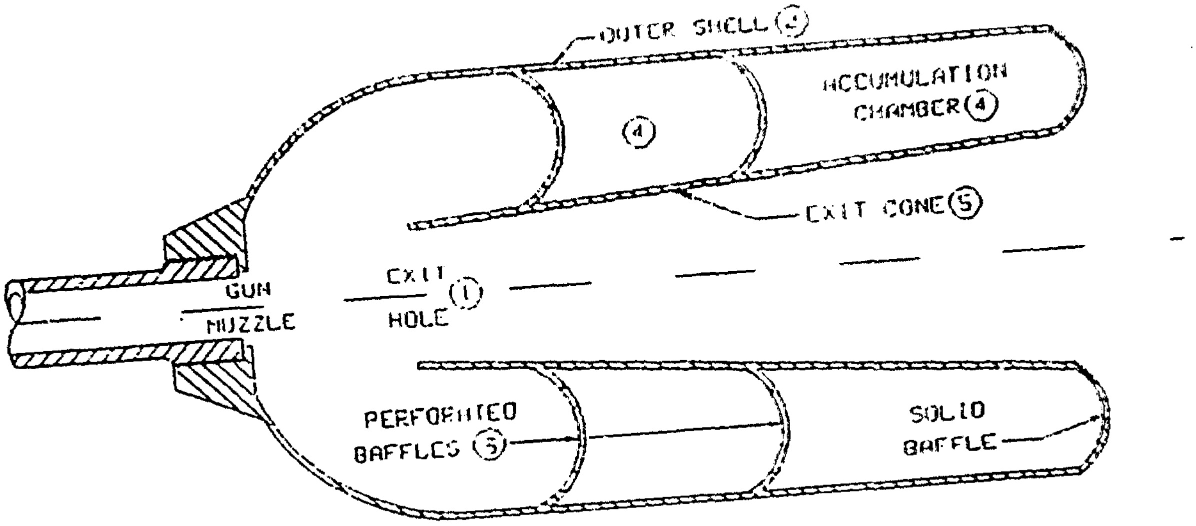


Figure 1. A Muffler Design for Guns that Fire Saboted Projectiles.

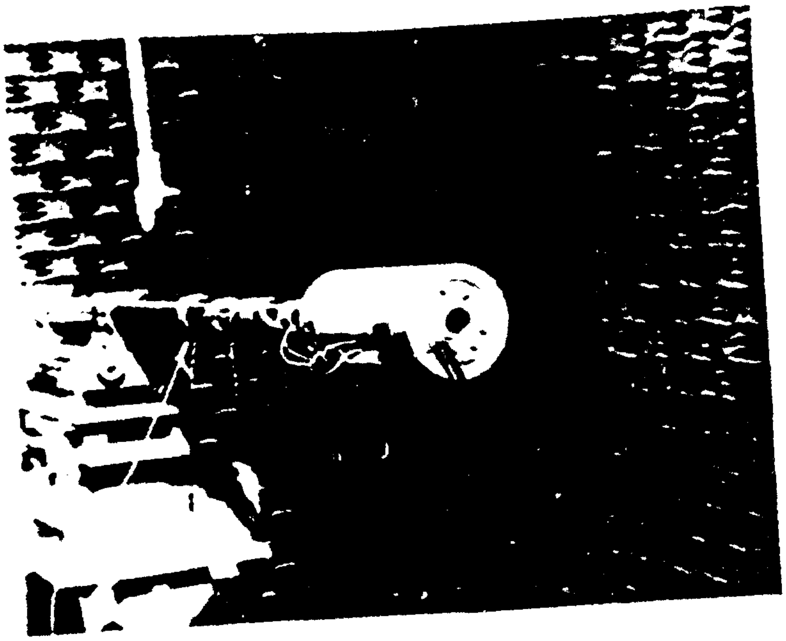


Figure 2. Smallest Muffler, Set Up for a Blast Overpressure Test.

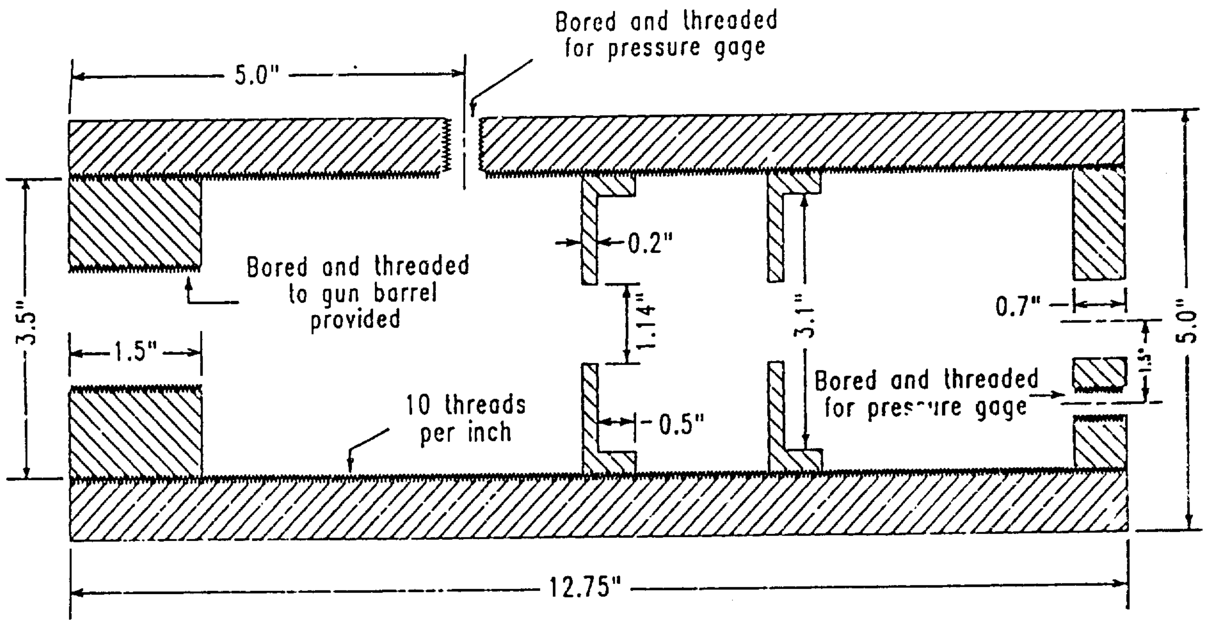


Figure 3. Drawing of Smallest Noise Attenuator Studied.

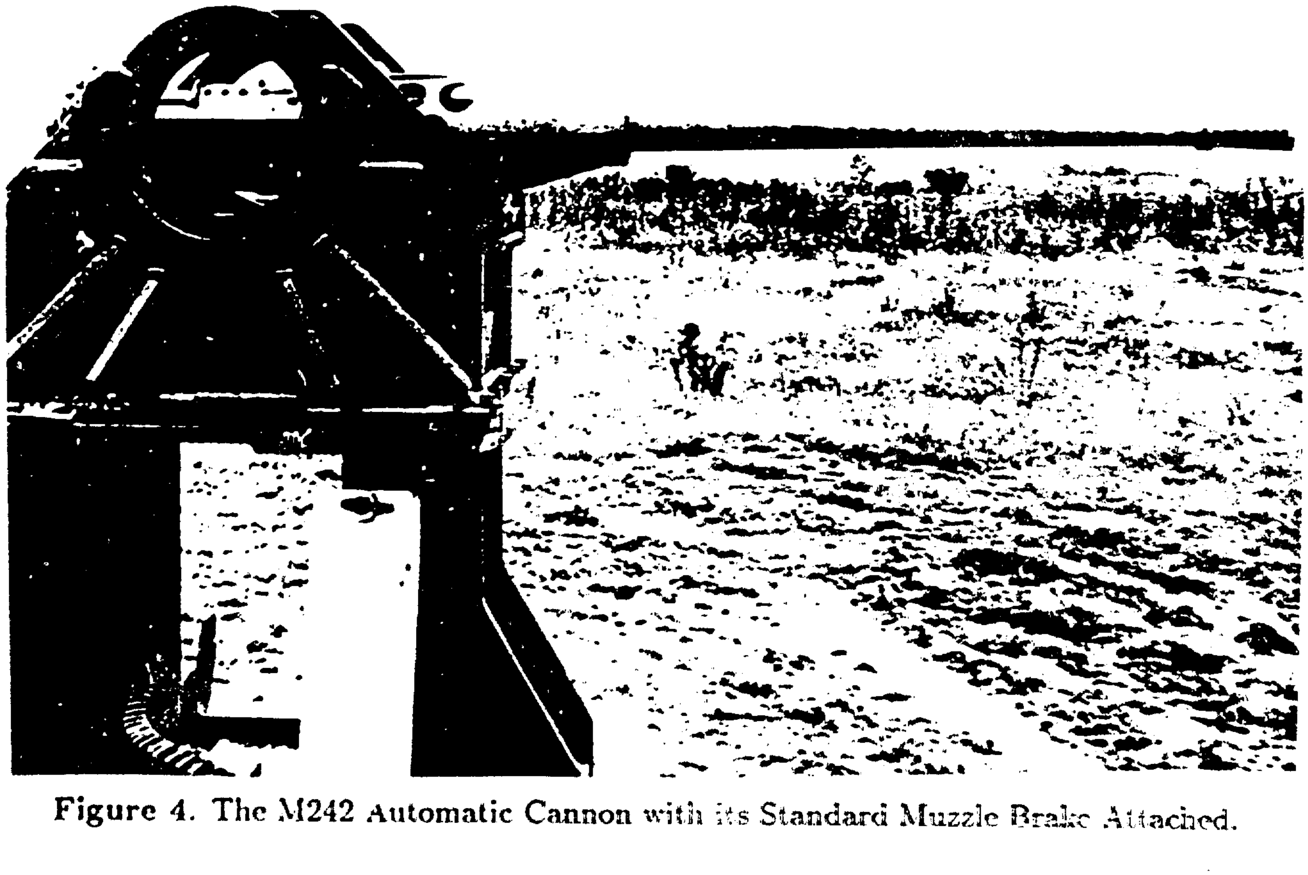
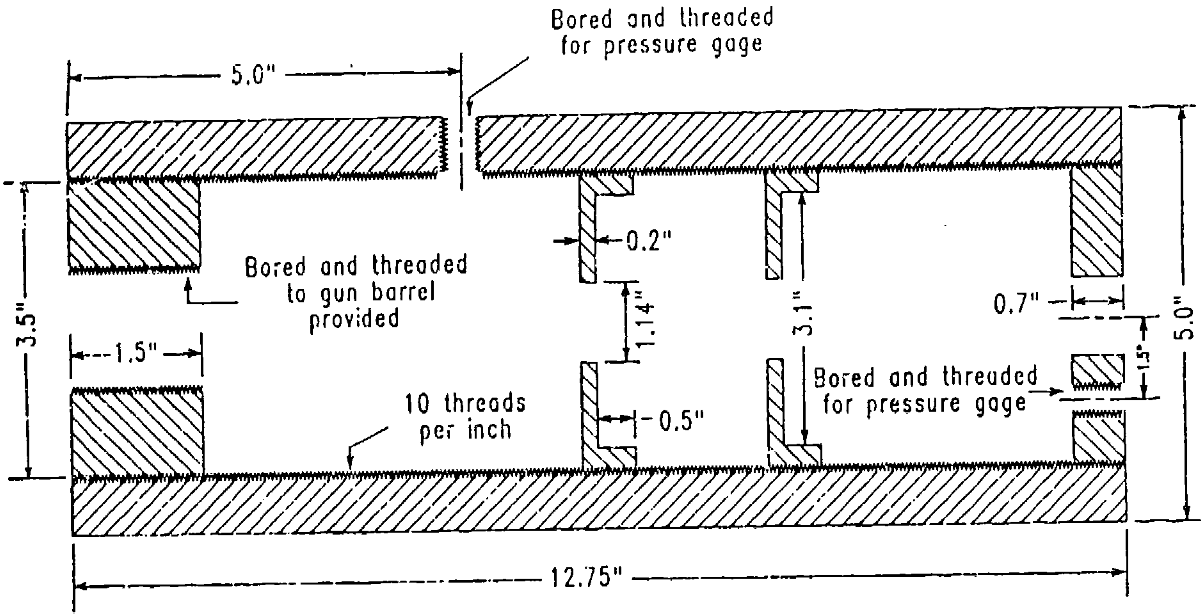


Figure 4. The M242 Automatic Cannon with its Standard Muzzle Brake Attached.



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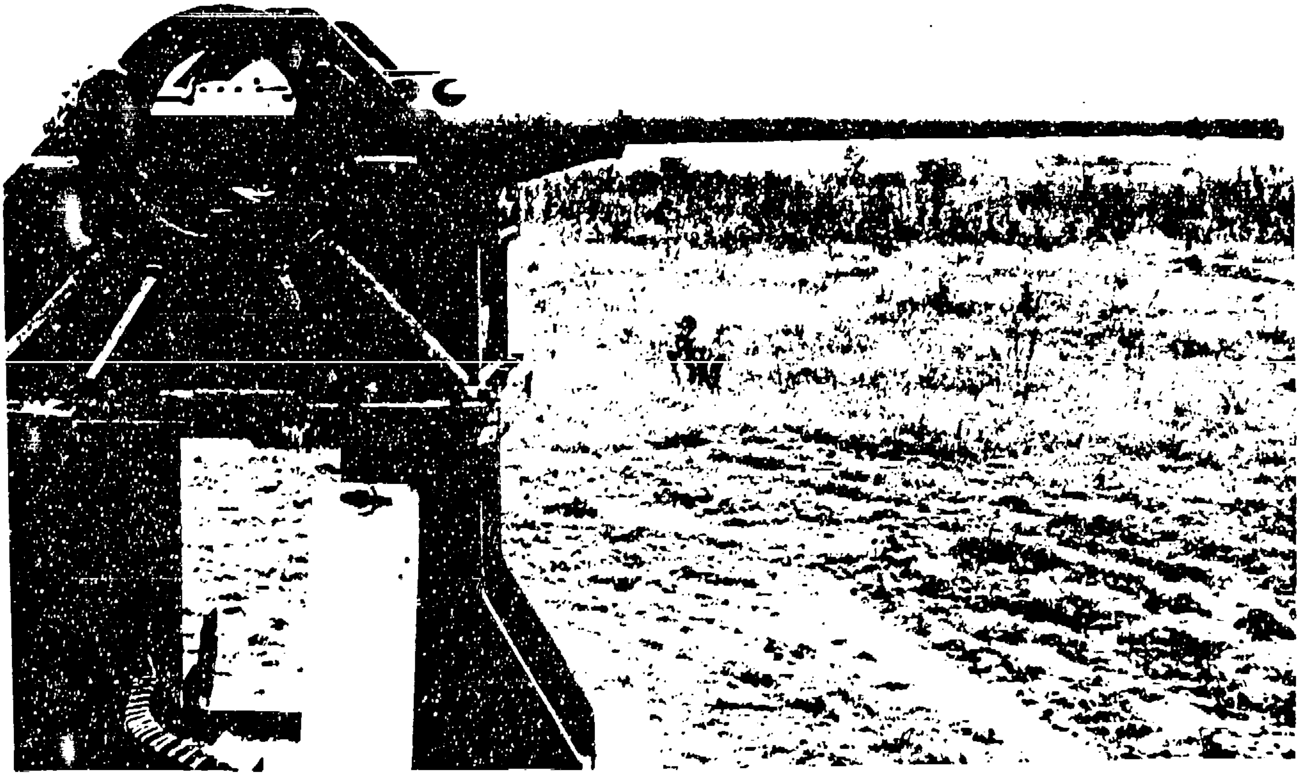

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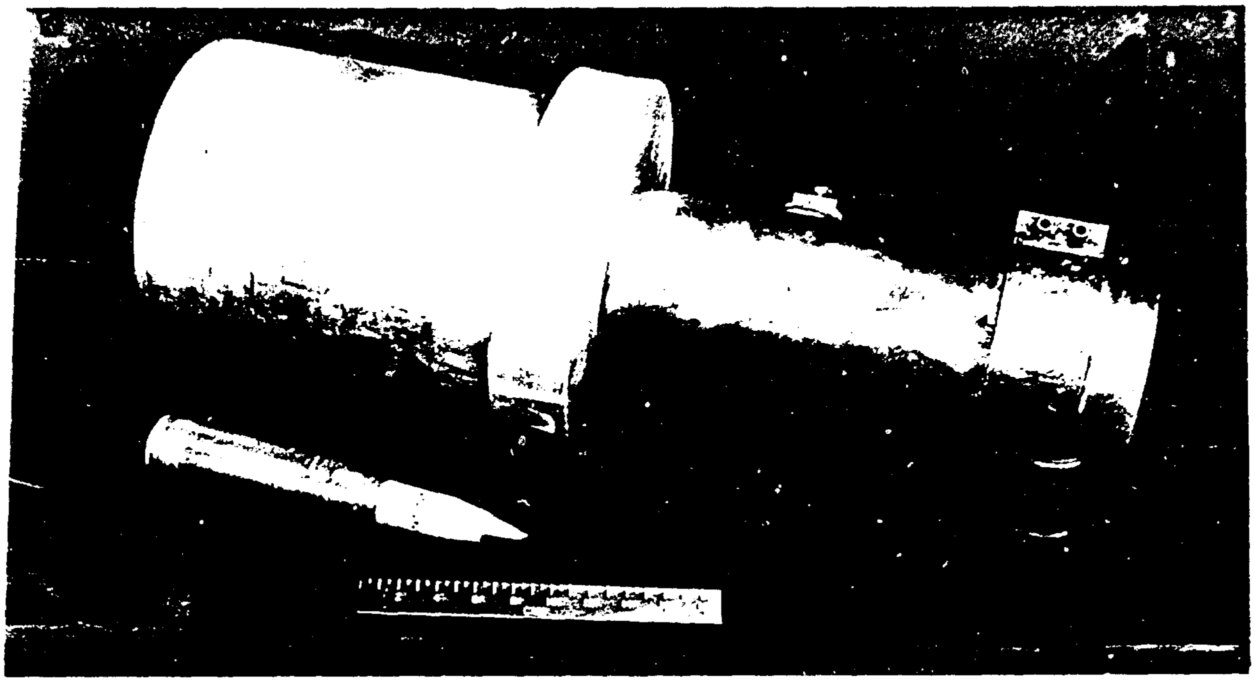

Figure 5. Photograph of the 6-Gun-Volume Muffler.

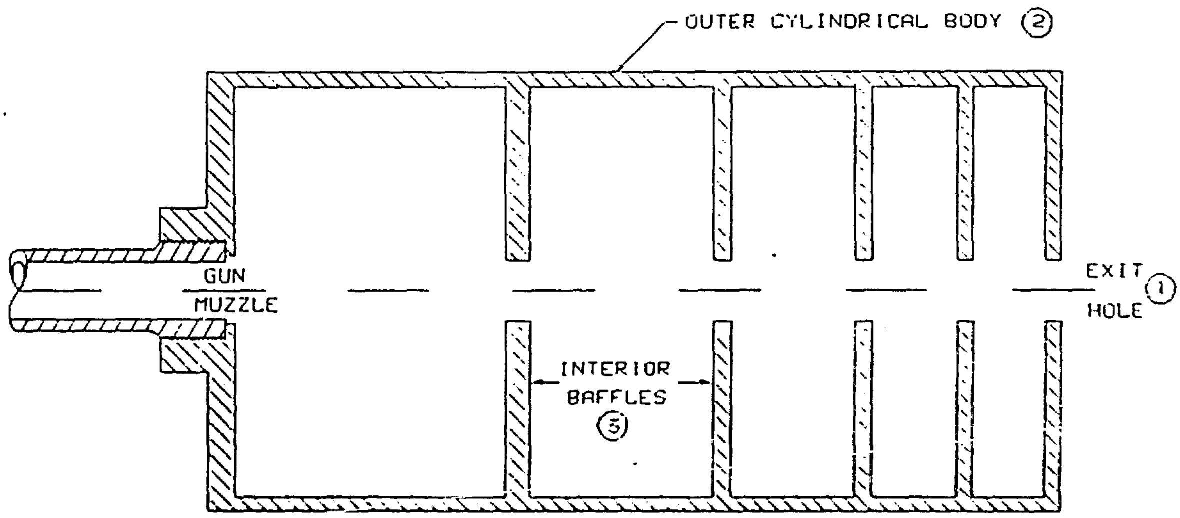

Figure 6. Drawing of the 9-Gun-Volume Muffler.

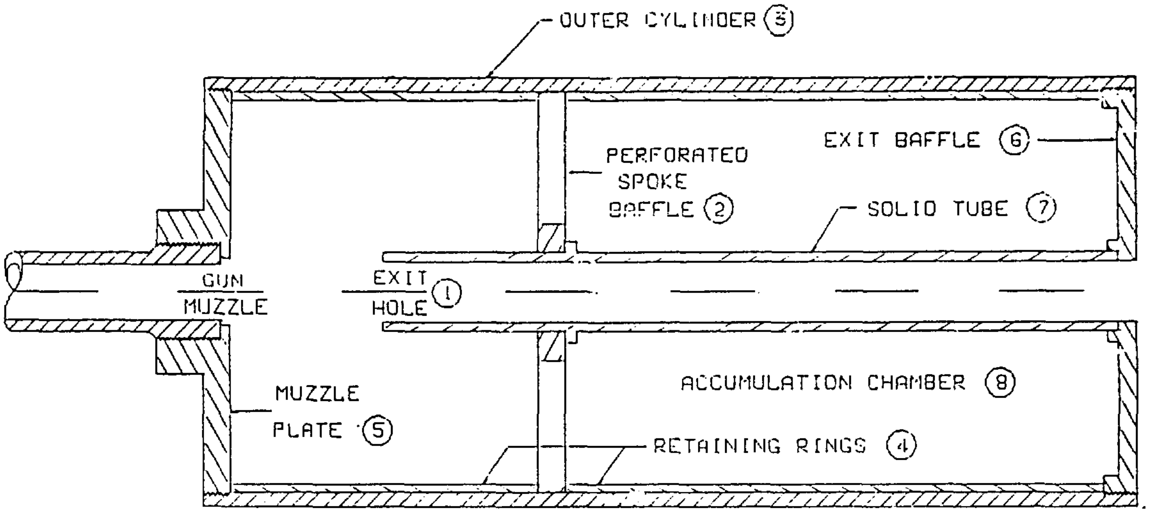

Figure 7. Configuration for Studying the Expected Performance of a Muffler Capable of Passing Sabots Through the Device with Minimal Interference.

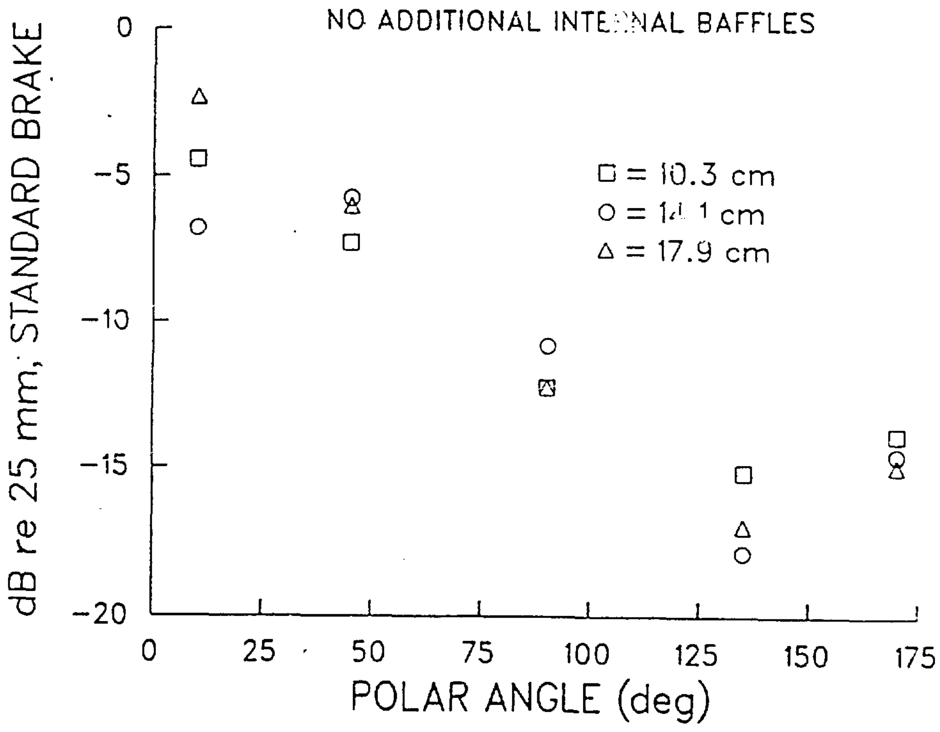

Figure 8. Attenuation Levels for Different Inlet Length of the Smallest Muffler. (Maximum Internal Length Configuration)

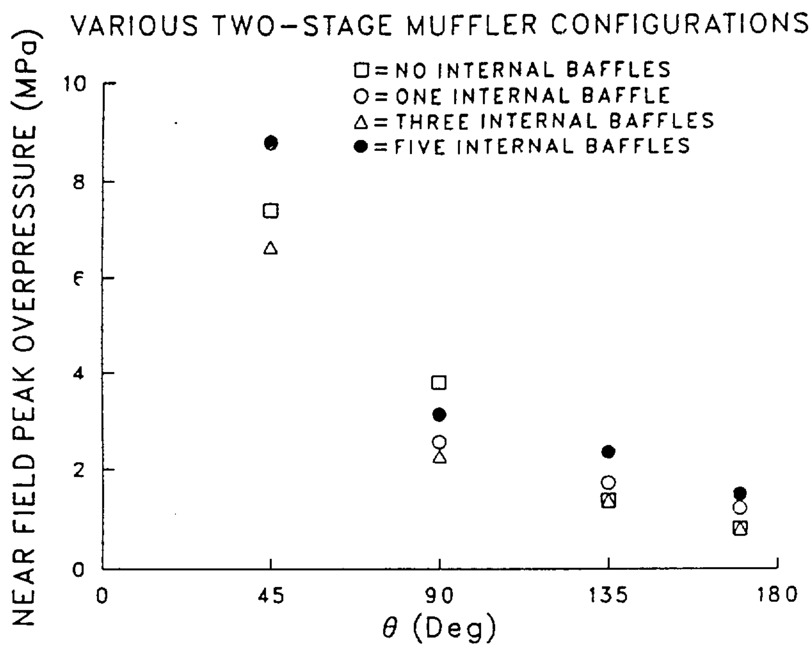

Figure 9. Dependence of Near Field Peak Overpressure Levels for Different Numbers of Baffles Using the 6-Gun-Volume Muffler.

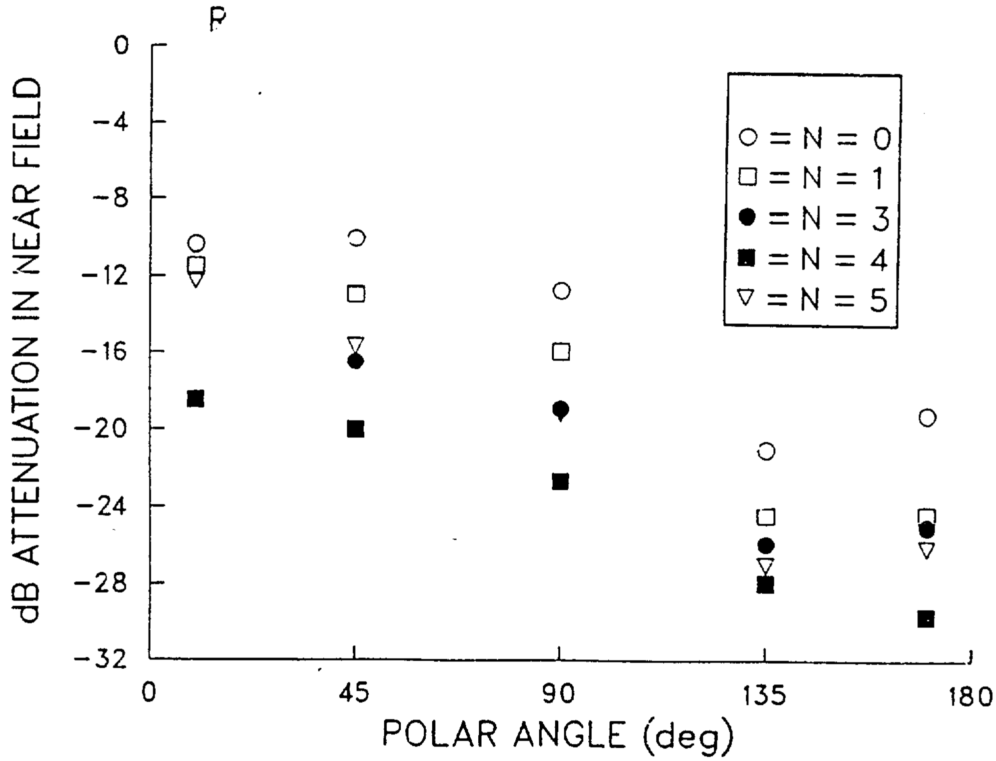

Figure 10. Attenuation Levels for Different Numbers of Baffles. 9-Gun-Volume Muffler.

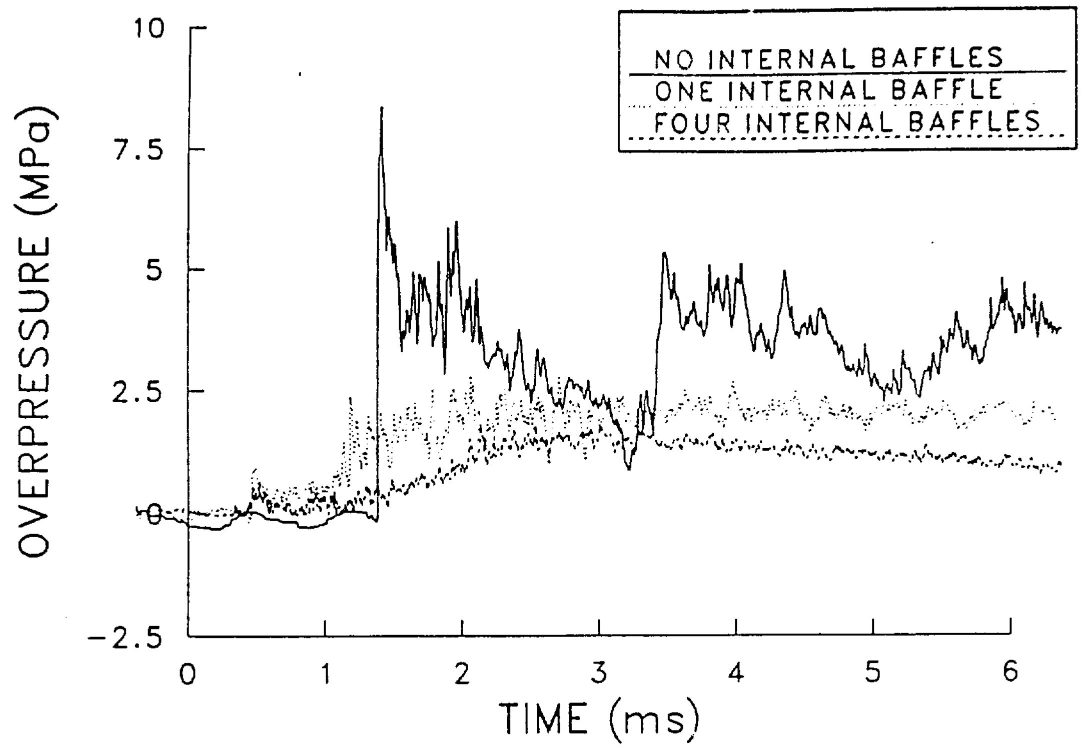

Figure 11. Exit Baffle Pressure as a Function of Time for Various Configurations of the 9-Gun-Volume Muffler.

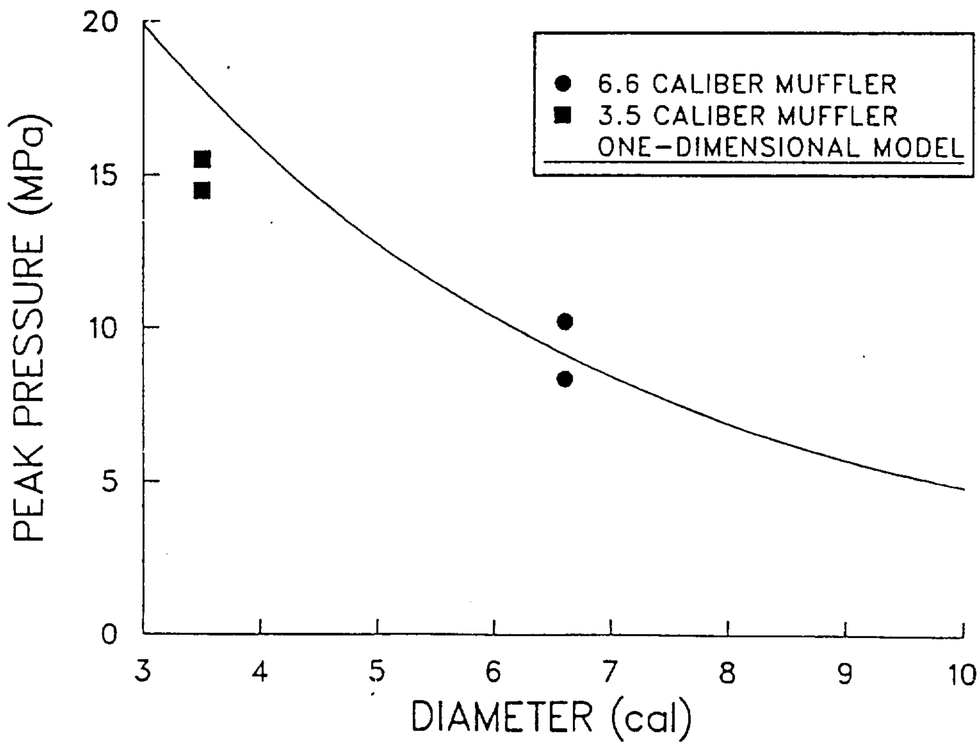

Figure 12. Exit Baffle Peak Pressure versus Internal Diameter for Mufflers with no Internal Baffle.

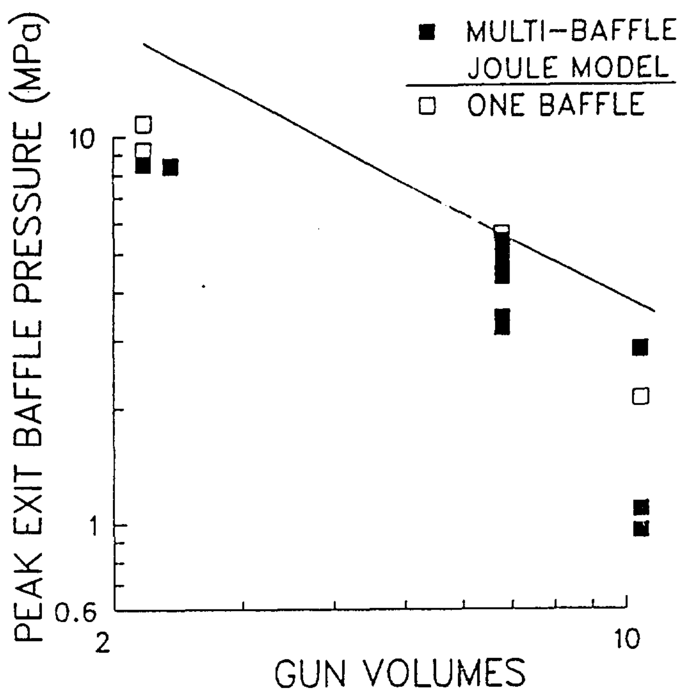

Figure 13. Peak Exit Baffle Pressure versus Total Internal Volume of Gun-Muffler System.

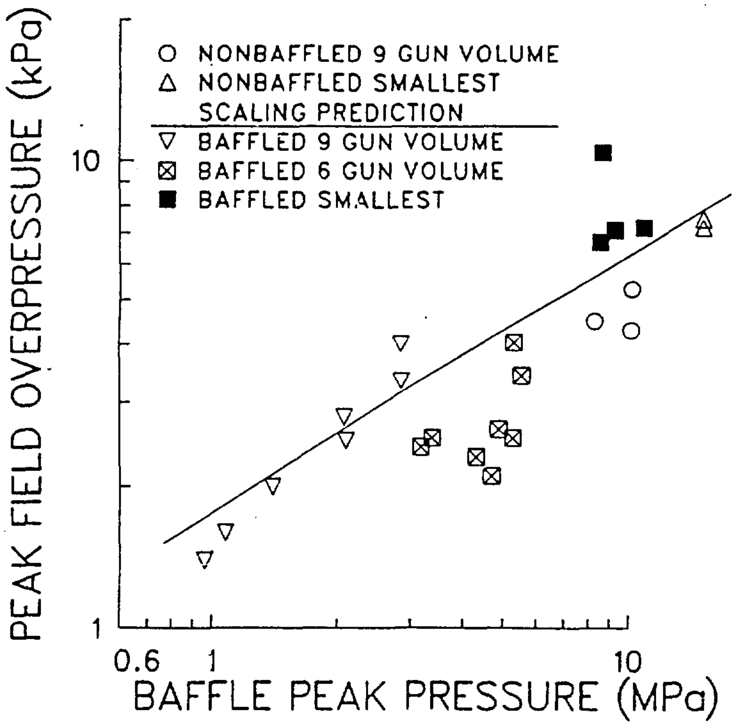

Figure 14. Peak Free-Field Overpressure at 90 degrees versus the Exit Baffle Peak Pressure.

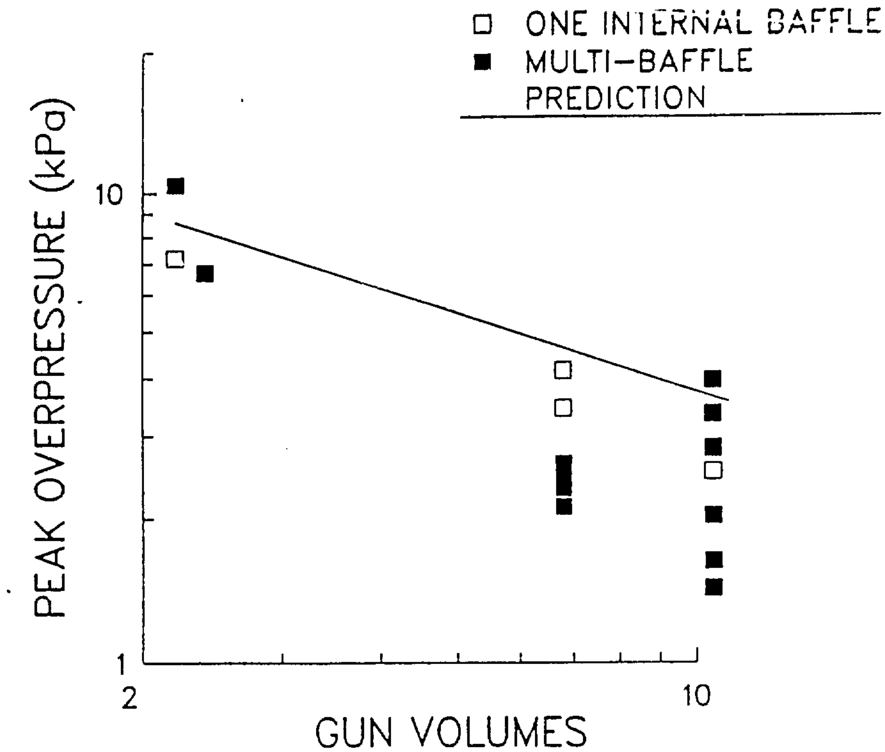

Figure 15. Peak Free-Field Overpressure at 90 degrees versus Volume of Gun-Muffler System.

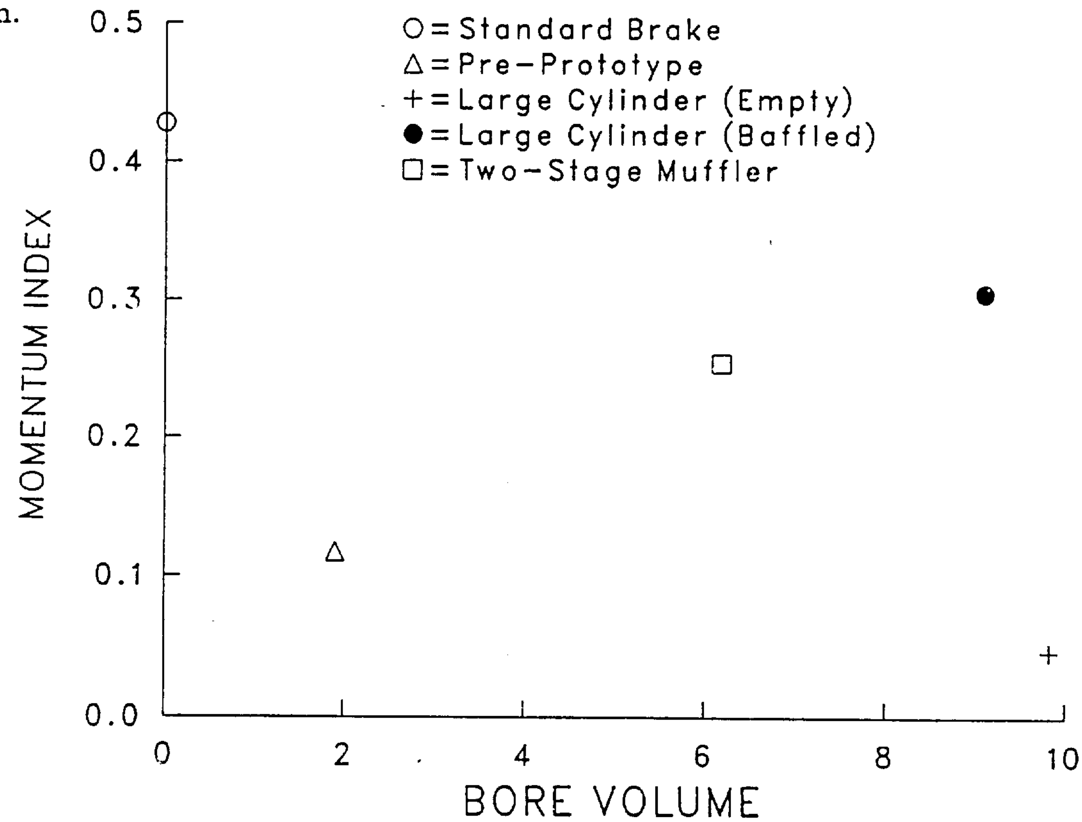

Figure 16. Momentum Index versus the Total Internal Volume of Gun-Muffler System. (Momentum Index is a Measure of the Braking Effectiveness.)

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